Investigating cluster structures in the A=10 mass region via ^{10}B + ^{10}B nuclear reactions

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Abstract. The selectivity of the ^{10}B + ^{10}B reactions in populating different states of neighboring nuclei was studied at beam energies of 50.0 and 72.2 MeV. The peculiar structure of ^{10}B, which can be described as a mixture of shell model and cluster configurations of the type ^{6}Li$_{gs}$ + α or ^{6}Li(0_2^+,1) + α [1], together with a high spin of the ground state $J^\pi = 3^+$, enabled the population of various high-spin and high-excitation energy states in nuclei around $A = 10$. We report and discuss the new and rarely observed states populated in ^{12,13}C, ^{14}N, and ^{16}O.

1 Introduction

Revealing the detailed structure of various nuclear states and developing a comprehensive spectroscopic picture for nuclei near $A = 10$ is of significant importance. In this mass region, states that are primarily characterized by shell-model often coexist and mix with molecular and cluster structures, leading to a rich variety of configurations (see the review paper [2] and references therein). In previous years, nuclei in this region have become accessible through *ab initio* calculations, allowing them to serve as ideal testing grounds for the refinement of theoretical nuclear models. Additionally, states in nuclei around $A = 10$ are important for astrophysical and cosmological models due to their role in various phases of stellar evolution.

The high-energy region of isotopes in this mass region exhibits a dense concentration of states with significant overlap, posing a particular challenge for investigation. Accurate identification of these states is important for disentangling the rotational bands of highly deformed cluster structures and recognizing their high-spin constituents (e.g. [3]). Well-defined states preferentially populated in specific experimental channels within this high-energy region not only offer insights into structural characteristics but also serve as compelling evidence thereof. While reaching high-spin states is not always feasible, the unique conditions of the experiment presented here, allow for the population of such states in the exit channels.

Among light nuclei, ^{12}C is of particular importance due to its role in stellar nucleosynthesis, especially through the Hoyle state at $E_x = 7.65$ MeV, which facilitates helium burning and the formation of heavier elements [4, 5]. Neighboring ^{13}C provides insight into the structural impact of an additional nucleon, with shell model predictions holding well up to ≈10 MeV, after which cluster configurations, such as ^{9}Be + α, become significant [6–9].

Structurally, ^{14}N is an intriguing nucleus, with linear-chain configurations predicted in analogy with similar states in ^{14}C [10, 11]. Recent studies by Kanada-En'yo [12] investigated a rotational band in ^{14}N based on a deformed structure of the type ^{10}B + α. This band includes an enhanced linear-chain 3α configuration, where an α cluster is localized along the longitudinal axis of the deformed ^{10}B core, providing a unique insight into possible chain structures in light nuclei.

New spectroscopic data for excited states of ^{14}N above the α-threshold were obtained through an extensive R-matrix analysis of α + ^{10}B scattering and charge-exchange reaction data [13]. These data extend only up to an excitation energy of 13 MeV and indicate the presence of clustered states in ^{14}N that could significantly enhance the rates of α-capture reactions on boron isotopes. Such reactions may have important implications for nucleosynthesis processes in first-generation stars.

The structure of ^{16}O has long been of interest in the field, particularly regarding the four α-chain state initially proposed by Chevallier *et al.* [14]. This structure suggests a linear chain of four α-particles rotating as a rigid system, with expected resonances from 2^+ to 6^+ in the 16–21 MeV range and a possible 8^+ state around 21.3 MeV [15–17]. However, multiple experimental and theoretical studies have shown that this linear chain structure does not adequately describe ^{16}O, instead suggesting a different configurations ([18] and references therein).

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Of particular interest is the $K^\pi = 0^+$ 4p–4h rotational band, with a band-head at 6.049 MeV [19]. This band is believed to have an α + ^{12}C configuration [20] and is challenging to distinguish experimentally from states with different α-cluster compositions.

Numerous theoretical models, including Hartree-Fock (HF) [21, 22], Nilsson–Strutinsky (NS) [23], and the Bloch–Brink α-cluster model [24], have been applied to classify ^{16}O states, with a common feature being the first excited state at 6.049 MeV (0^+), which lies close to the α-decay threshold. This state is described by both NS and HF calculations as a 4p–4h excitation, reflecting an α-particle excitation to the sd-shell.

Mirror nuclei, pairs of isobars where the proton number in one equals the neutron number in the other ($Z_1 = N_2$ and $Z_2 = N_1$), provide further insight into nuclear structure and charge independence of nuclear forces. Studies on mirror pairs like ^{13}C and ^{13}N show how the Coulomb displacement energy is influenced by the spatial configuration of valence particles, with more compact orbitals experiencing a greater Coulomb shift [25, 26]. This research, which initially focused on bound states, has expanded to include resonant states and cluster structures, demonstrating the importance of different configurations in contributing to the Coulomb energy. Despite the progress, experimental data on cluster states in mirror nuclei remain limited, especially for states populated simultaneously in the same experiment. The ^{10}B + ^{10}B reaction used in this study, provides an ideal scenario for populating mirror pairs in the exit channels.

2 Experiment

The ^{10}B+^{10}B experiment was carried out at the INFN-LNS facility in Catania, employing the SMP Tandem accelerator to deliver a highly focused ^{10}B beam (beam diameter 1 mm) at energies of 50.0 and 72.2 MeV onto targets enriched to 99.8% ^{10}B. Reaction products were detected using four ΔE-E silicon telescopes, each composed of a thin ΔE detector (57-67 μm) and a thick double-sided silicon strip detector (DSSSD) with thicknesses of either 500 or 1000 μm. Each DSSSD was segmented into 16 strips on both the front and back faces, offering high angular resolution and minimizing noise by comparing front and back signals within a 3% tolerance. Schematic view of the setup is given in Figure. 1.

Three distinct detector arrangements were implemented to optimize the detection across a wide range of reaction exit channels and excitation energies, with polar angles of detector centers spanning from 20° to 53°. Data were recorded in both single and coincidence modes, allowing for a comprehensive analysis of reaction channels. Despite the aim to observe four-particle coincidences, the experiment encountered statistical limitations, though a high yield of α-particles was achieved. Triple α-particle coincidences were recorded with significant statistics, while the ΔE-E technique provided clear particle identification, distinguishing isotopes from hydrogen to carbon.

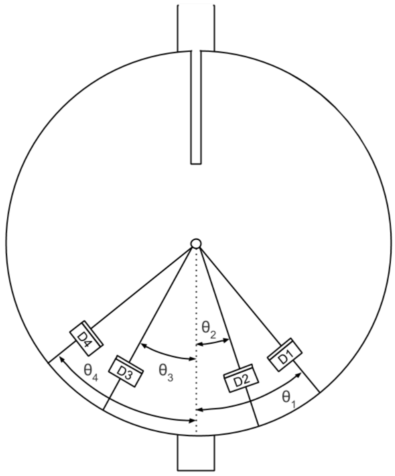

Figure 1. Shematic view of the experimental setup inside the chamber, with four ΔE-E telescopes. Polar angles Θ were changed three time during experiment.

Monte Carlo simulations were employed to assess detection efficiencies, modeling the two-body ^{10}B+^{10}B reaction and assuming isotropic center-of-mass distributions for sequential decay fragments [27]. This simulation framework allowed accurate estimation of angular acceptance and energy thresholds across the experimental setup, resulting in a robust and detailed dataset for investigating nuclear structure in this mass region.

3 Results for ^{12}C and ^{13}C

The primary findings from this measurement include the identification of new states in ^{12}C and ^{13}C. As these results have already been published [28, 29], we provide here a brief overview of the key outcomes for these nuclei.

Thanks to the large solid angle and high segmentation of the detector setup, high statistics in double and triple α-particles coincidences were achieved, allowing systematic exploration of ^{10}B + ^{10}B → 5α channels and associated decay pathways.

For ^{12}C, detection of two α-particles in coincidences allowed for the reconstruction of its excitation energy spectrum by assuming a three-body reaction. This spectrum revealed several prominent states, such as the 0^+ ground state, the 2^+ state at 4.44 MeV, the 3^- state at 9.64 MeV, and the Hoyle state at 7.65 MeV. Higher excitation states, including a significant peak at 24.4 MeV and others at 22.4 MeV and 30.3 MeV, were observed and consistently populated across multiple detector setups. Detection of the three α-particles in coincidences revealed the ^{12}C states above the 3α-emission threshold, in particular, a new state of ^{12}C at E_x = 24.4 MeV, discussed and reported for the fist time in [28]. The rarely seen state at E_x = 30.3 MeV is found to be strong in the d+^{10}B decay channel, reinforcing the previous suggestions that it has the exotic 2α+2d molecular structure [30].

In the case of ^{13}C, the nucleus was produced via direct nucleon pick-up or stripping reactions, and its states were reconstructed by detecting either single ^{7}Be events, or an α particles and ^{9}Be in coincidence. In the single-mode analysis, all ^{13}C states, starting from the ground state, were populated without constraints on decay mode. This method highlighted states above the α-emission threshold at 10.648 MeV, where a 19.0 MeV state emerged, with a width of approximately 660 keV. The second data set, gathered in coincidence mode, further confirmed the presence of the 19.0 MeV state. This state is observed with similar width and excitation energy across different detector configurations, always dominating the high-energy region, distinguishing itself from previously cataloged ^{13}C states and suggesting the identification of a new resonance [29].

4 Results for ^{14}N

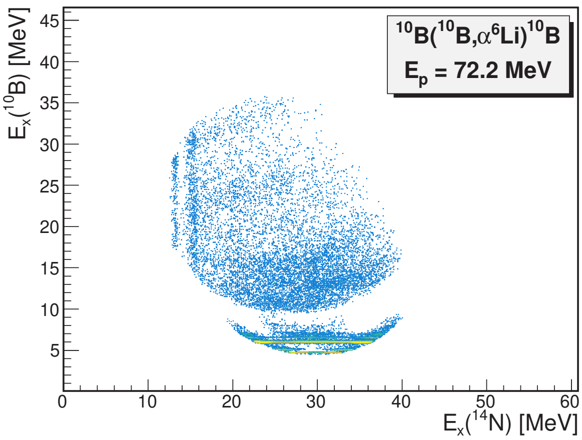

Figure 2. Dalitz plot showing the excitation energy of ^{14}N plotted against that of ^{10}B, for all events from the reaction ^{10}B(^{10}B, α^{6}Li)^{10}B, with undetected ^{10}B left in its ground state.

Due to the complex structure of the ^{10}B projectile and target nuclei, α-transfer into states of ^{14}N was strongly observed. In the exit channel ^{6}Li + α + ^{10}B, different two-body intermediate steps were considered, requiring the relative energies (or corresponding excitation energies) of all three possible pairs to be plotted (*i.e.*, effectively Dalitz plots), as shown in Fig. 2. Many horizontal lines in the lower part of the plot correspond to low excitation states of ^{10}B, while two vertical lines arise from intermediate ^{14}N excitations.

By applying a gate on events with E$_x$(^{10}B)>15.0 MeV, to avoid mixing with low-energy states in ^{10}B, we obtained the excitation spectra of ^{14}N (Fig. 3). Various detector combinations and setups were employed, but ^{6}Li was always detected at azimuthal angles greater than 40°. The energy of ^{14}N was calculated from the detected ^{6}Li and α particle, with a gate applied on the ground state of the missing mass partner ^{10}B.

Two pronounced states of ^{14}N are seen in Fig. 3 at E$_x$ = 13.19 and 15.36 MeV, decaying through the ^{10}B + α channel. The first one is the well-known α-decaying 3$^+$ state, initially observed as a strong resonance in α + ^{10}B reactions [31, 32], with a measured width $\Gamma \approx 200$ keV, whereas its nominal width is smaller ($\Gamma = 65$ keV) [33], indicating the resolution limitations of our setup. The second state is not reported at the exact energy seen here (15.36 MeV), although two α-decaying states at close excitation energies (15.24 and 15.43 MeV) with smaller widths (100 keV) are listed in [33].

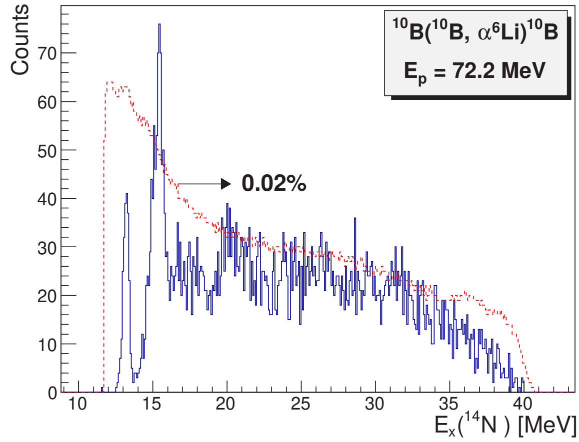

Figure 3. Excitation spectra of ^{14}N obtained from the coincident detection of α and ^{6}Li, with undetected ^{10}B left in its ground state. Different detectors combinations and setups are combined. The (red) dotted line shows the corresponding Monte Carlo efficiency curve. The absolute value of efficiency is given for a single point of the curve, so that it can be inferred for the rest of it.

Recent studies suggest that the 13.2 MeV state may be the head of a rotational band $K^\pi = 3^+$, based on a ^{10}B(3$^+$)+ α structure [12]. The observed state at 15.36 MeV (which is a rarely observed state), most likely corresponds to the 5$^+$ member of this rotational band. These states, described by a ^{10}B(3$^+$) + α structure, align with predictions from antisymmetrized molecular dynamics (AMD) models, which suggest a complex structure with a prominent linear-chain 3α-component where the α-cluster aligns along the longitudinal axis of the deformed ^{10}B cluster.

Additionally, ^{14}N states were observed in the channel ^{10}B(^{10}B, $d\,^{6}$Li)^{12}C, at excitation energies of 11.75 and 13.0 MeV (Fig. 4). Consistent with the tabulated values [33], these states decay via p- and d-channels, with a structure similar to the α-decaying states due to the $\alpha + \alpha + \alpha + d$ component of the excited ^{14}N states.

5 Results for ^{16}O

States of the ^{16}O nucleus were observed in the ^{10}B(^{10}B, α^{12}C) reaction when ^{12}C and α-particle were detected in coincidence. The Q-spectrum for this channel revealed two prominent states, with the stronger line corresponding to the excitation of ^{12}C to the 2$^+$ state at 4.44 MeV, resulting in a Q-value of $Q_1 = 14.07$ MeV.

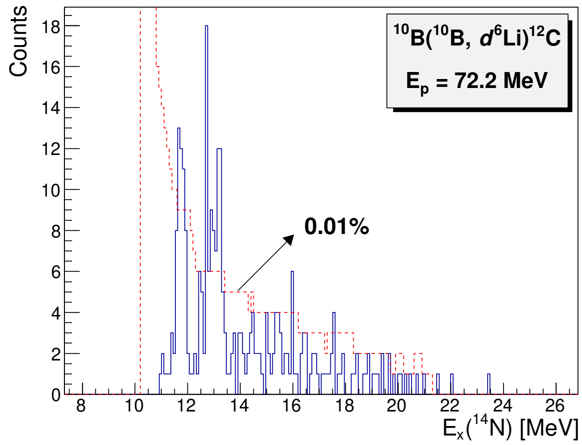

Figure 4. Excitation spectra of ^{14}N obtained by detecting d and ^{6}Li in coincidence, in different detector combinations and setups. The undetected ^{12}C is left in its ground state. The (red) dotted line shows the corresponding Monte Carlo efficiency curve.

As shown in Fig. 5, three states of ^{16}O appear at excitation energies of 17.53, 20.33 and 26.44 MeV, each with a relatively broad width. These states decay through the first excited state of ^{12}C at 4.44 MeV and are positioned close to other broad states at similar excitation energies. The states at 17.53 and 26.44 MeV have been previously identified in ^{12}C(α, α')^{12}C scattering experiments [33], while the state at 20.33 MeV likely represents a combination of closely spaced, broad states in this region.

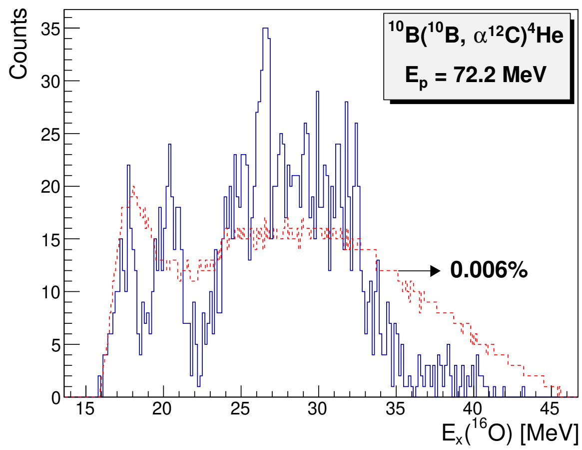

Figure 5. Excitation spectra of ^{16}O obtained by detecting α and ^{12}C in coincidence, in different detector combinations and setups. The undetected ^{4}He is left in its ground state, but the detected ^{12}C is in its first excited state at 4.44 MeV.The (red) dotted line shows the corresponding Monte Carlo efficiency curve.

6 Study of mirror nuclei

The reaction ^{10}B + ^{10}B provides a valuable approach to investigate high-energy, high-spin states in mirror nuclei pairs, specifically ^{9}Be-^{9}B, ^{10}Be-^{10}C, and ^{11}B-^{11}C. Through examining these relatively simple systems, insights into spatial and quantum symmetries in nuclei are achievable, enhancing our understanding of fine aspects of strong nuclear interactions.

For the mirror nuclei ^{9}B and ^{9}Be, the excitation energy spectra reveal an absence of the first excited states (1/2^{+}), known for their strongly clustered configurations based on σ-orbital. However, states that correspond to the rotational bands of their ground states (3/2^{-}) are visible, identified as the 9/2^{-} members in both nuclei.

In the ^{10}B(^{10}B,^{10}Be)^{10}C channel, inclusive spectra offer an examination of the ^{10}Be-^{10}C mirror pair. Several peaks correspond to recognized states in ^{10}C and ^{10}Be, including a notable state observed in ^{10}C at approximately 9.5 MeV. This state appears to correspond to the ^{10}C excitation at E_x = 9.45 MeV, an isospin analog of the 2^{+} state in ^{10}Be at E_x = 9.56 MeV, which has not been reported in recent ^{10}C studies [34] or in the TUNL compilation [35].

The third mirror pair, observed through an experimental setup with segmented strip detectors suited for multiple coincidence studies, involves ^{11}B and its mirror counterpart. The Q-value spectrum obtained from triple coincidences of α+α+p reveals states in ^{11}B selectively populated in the ^{10}B(^{10}B,^{9}B$_{g.s.}$)^{11}B reaction. Given that ^{9}B is unbound, this reaction represents a novel measurement, and the excited ^{11}B states serve as mirror counterparts to those observed in ^{11}C from the ^{10}B(^{10}B,^{9}Be)^{11}C reaction [27]. Several higher-energy states are also identified that were not reported in previous one-nucleon transfer reactions.

A comprehensive analysis of these mirror nuclei findings will be detailed in an upcoming publication.

7 Conclusion

In this study, nucleon transfer reactions between ^{10}B nuclei were explored. High-spin states were effectively populated, emerging prominently above 10 MeV in excitation energy, due to the J^{π} = 3^{+} ground state of ^{10}B. In ^{10}B + ^{10}B reactions we see strong two and three particles transfer to states of ^{12,13}C [28, 29], an α-tranfer to states of ^{14}N and a six nucleon transfer to ^{16}O.

In particular, a new state of ^{12}C at E_x = 24.4 MeV is strongly populated in the triple α-particle coincidences, while the rarely seen state at E_x = 30.3 MeV is found to be strong in the d + ^{10}B decay channel, reinforcing the previous suggestions that it has the exotic 2α + 2d molecular structure [30]. Regarding the ^{13}C nucleus, a potentially novel state at Ex = 19.0 MeV is prominently observed in α + ^{9}Be coincidences and demonstrates a well-defined cluster structure. Furthermore, in four nucleons transfer reaction channel, excited states of the ^{14}N at E_x = 13.2 and 15.36 MeV were measured.

Lastly, the unique opportunity presented by ^{10}B + ^{10}B reactions to study high-energy, high-spin states in mirror nuclei pairs such as ^{9}Be-^{9}B, ^{10}Be-^{10}C and ^{11}B-^{11}C is explored. By comparing these relatively simple nuclei, one can probe spatial and quantum symmetries within nuclei, which offer insights into fine details of strong nuclear interactions.

This work has enhanced the understanding of high-spin and cluster structures in the A = 10 region and highlighted the potential of the ^{10}B + ^{10}B reaction for further exploration of nuclear configurations.

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